Workshop on the Intermediate Neutrino Program 2015

Experimental Program at the Fermilab Long-Baseline Neutrino Facility

An international collaboration to design, build and operate an experimental program at the Fermilab Long-Baseline Facility (ELBNF) is in the process of forming. The responses to the WINP 2015 questionnaire were drawn from the Letter of Interest submitted to the Fermilab PAC 22 December 2015, from the first meeting of the collaboration held 22-23 January 2015 and from documents prepared by previous long-baseline collaborations and other groups who have come together to form the new collaboration. *Since the collaboration has yet to select spokespeople or formalize working groups <u>all responses should be considered preliminary</u>*.

1. Name of Experiment/Project/Collaboration: *tbd*

   For the purposes of this document we will use ***Experimental Program at the Fermilab Long-Baseline Neutrino Facility (ELBNF)*** *as a placeholder.*

2. Physics Goals

   a. Primary
   - *Observation of CP violation in lepton sector*
   - *Determination of the neutrino mass hierarchy*
   - *Measurement of neutrino oscillation parameters in 3-flavor paradigm esp. CP phase*
   - *Search for nucleon decay*
   - *Observation of neutrinos from core collapse supernovae*

   b. Secondary
   - *Precision measurements of neutrino interactions on various target nuclei*
   - *Measurement of solar neutrino flux*

3. Expected location of the experiment/project:

   Fermilab (Batavia, IL) and Sanford Underground Research Facility (Lead, SD).

4. Neutrino source:

   New 1.2 MW beamline at Fermilab (PIP-II).

5. Primary detector technology:

   Far detector: Liquid argon Time Projection Chamber

   Near detector: Fine-grained, low-mass straw tracker in magnetic field is the most well-developed and has a funding proposal pending. It has also been considered to add a liquid argon or high-pressure gas TPC. Other options and configurations will be considered.

6. Short description of the detector

   Total far detector fiducial mass will be 40 kt of liquid argon. This mass will be achieved in several steps, and may involve evolving technologies.

   The liquid argon time projection technology is chosen to allow high granularity event reconstruction with high particle identification capability with high efficiency.

   The readout of the liquid argon detector could be performed by drifting of the ionization electrons into wire chambers immersed in the liquid argon, this is referred to as a single phase TPC. Another choice in development is a double phase readout in which the ionization electrons produced in the liquid are extracted from the top surface of the liquid and measured in the argon gas above the liquid.

   The detector mass may implemented in modules of at least 5 kt (fiducial) each. The optimum size of these modules and associated underground civil construction in hard rock caverns at SURF is under discussion.

7. List key publications and/or archive entries describing the project/experiment.

   a. "An Experimental Program in Neutrinos, Nucleon Decay and Astroparticle Physics Enabled by the Fermilab Long-Baseline Neutrino Facility" A *Letter of Intent submitted to the Fermilab PAC. 22 December 2014*

   b. *The Long-Baseline Neutrino Experiment: Exploring Fundamental Symmetries of the Universe arXiv:1307.7335. This will be superseded by a Conceptual Design Report from the new collaboration later in 2015.*

   c. *LBNO-DEMO: Large-scale neutrino detector demonstrators for phased performance assessment in view of a long-baseline oscillation experiment. arXiv:1409.4405*

   d. *"Baseline optimization for the measurement of CP violation and mass hierarchy in a long-baseline neutrino oscillation experiment", arXiv:1311.0212 [hep-ex].*

8. Collaboration

   a. Institution list

      Alabama (US), Alfenas (Brazil), Aligarh Muslim (India), Antananarivo (Madagascar), APC-Paris (France), Argonne (US), Atlantico (Columbia), Banaras (India), Bern (Switzerland), Boston (US), Brookhaven (US), Brown (US), California-Berkeley (US), Caltech (US), Cambridge (UK), Campinas (Brazil), Catania (Italy), CBPF (Brazil), CERN (Switzerland), Charles (Czech Rep.), Chicago (US), Ciemat (Spain), Cincinnati (US), Cinvestav (Mexico), CNI Pisa (Italy), Colima (Mexico), Colorado (US), Colorado State (US), Columbia (US), Cornell (US), CTU (Czech Rep.), Dakota State (US), Davis (US), Delhi (India), Drexel (US), Duke (US), Durham (UK), ETHZ (Switzerland), Feire de Santana (Brazil), Fermilab (US), Goias (Brazil), Guwahati (India), Hamburg (Germany), Hawaii (US), Houston (US), HRI (India), Huddersfield (UK), Hyderabad (India), Idaho State (US), IFAE (Spain), IIT (US), Illinois (US), Imperial (UK), Indiana (US), INFN Milano (Italy), INFN Napoli (Italy), INFN Padova (Italy), INFN Pavia (Italy), INR (Russia), IOP, Acad.Sci. (Czech Rep.), Iowa State (US), IPM (Iran), IPMU (Japan), Irvine (US), Jammu (India), Kansas State (US), KEK

(Japan), Kiev (Ukraine), Koneru Lakshmaiah (India), Krakow (Poland), Lancaster (UK), LAPP (France), LBNL (US), Liege (Belgium), Liverpool (UK), LNGS (Italy), Los Alamos (US), Louisianna State (US), Lucknow (India), Manchester (UK), Maryland (US), Max Planck MPP (Germany), Mayaguez (Puerto Rico), Michigan State (US), Milano-Bicocca (Italy), Minnesota (US), Minnesota-Duluth (US), MIT (US), Nehru (India), New Mexico (US), NIKHEF (Netherlands), Northwestern (US), Notre Dame (US), Observatorio Nacional (Brazil), Ohio State (US), Oregon State (US), Oxford (UK), Panjab (India), Penn State (US), Pennsylvania (US), Pisa (Italy), Pittsburgh (US), PNNL (US), Princeton (US), PUCP (Peru), Punjab Agricultural (India), RAL (UK), Rochester (US), Saclay (France), SDSMT (US), SDSTA (US), Sheffield (UK), SLAC (US), SMU (US), Sofia (Bulgaria), South Carolina (US), South Dakota (US), South Dakota State (US), Stanford (US), Stony Brook (US), Sussex (UK), Syracuse (US), Tennessee (US), Texas-Arlington (US), Texas-Austin (US), TUBITAK (Turkey), Tufts (US), UCL (UK), UCLA (US), UFABC (Brazil), Valencia (Spain), VECC (India), Virginia Tech (US), Warsaw (Poland), Warsaw NCNR (Poland), Warwick (UK), Wichita State (US), William and Mary (US), Wisconsin (US), Wroclaw (Poland), Yale (US), Yerevan (Armenia), York (Canada)

b. Number of present collaborators:

   The collaboration formed 1/22/15 with the establishment of an Institution Board, with representatives from 143 institutions. A formal collaboration list has not yet been collated, however there were 527 signatories to the ELBNF LOI submitted to the Fermilab PAC.

   https://indico.fnal.gov/confRegistrantsDisplay.py/list?order=down&sessionShowNoValue=1&sortBy=Institution&confId=9090#results

c. Number of collaborators needed.

   800-1000

9. R&D

   a. List the topics that will be investigated and that have been completed

      Completed: Prior to the focus on liquid argon by both the US-based LBNE and Europe-based LAGUNA-LBNO a substantial R&D program towards very large water Cerenkov and liquid scintillator detectors (arXiv:1204.2295, http://laguna.ethz.ch:8080/Plone/deliverables/laguna-lbno-284518-deliverables). In the context of ELBNF these have been completed, but the results are being used in other experiments under development.

      An extensive program of R&D towards liquid argon detector has been underway for many years, beginning with the pioneering work of the ICARUS collaboration. The work continues and is being extended by the many programs that will be reported on at this workshop.

      Within the ELBNF collaboration: a 35 t single-phase prototype at Fermilab has almost completed construction. A cryostat to accommodate a double-phase prototype TPC of roughly 1mx1mx3m is under construction at CERN. Large-scale prototypes (>500 t LAr) are being developed for both single-phase and double-phase TPCs at the CERN neutrino platform.

   b. Which of these are crucial to the experiment.

All are required at various levels to inform the development of the full-scope ELBNF design and construction plans.

c. Time line

- *35 t single-phase prototype nearing completion – operation mid-2015.*
- *Double-phase prototype TPC of roughly 1mx1mx3m at CERN - operation planned in the coming year.*
- *Large-scale prototypes single-phase and double-phase TPCs at the CERN - operation before the 2019 long-shutdown.*

d. Benefit to future projects

Provides broad information on the design and operation of large-scale cryogenic detectors, reconstruction of charged particles or several species, calibration of liquid argon TPCs.

10. Primary physics goal expected results/sensitivity:

Details may be found in the references provided in Item 7. Below we provide a few representative plots.

a. For exclusion limit (such as sterile neutrino search), show 3-sigma and 5-sigma limits

b. For discovery potential (such as the Mass Hierarchy), show 3-sigma and 5-sigma.

c. For sensitivity plots, show 3-sigma and 5-sigma sensitivities

(note that for neutrino-less double beta decay experiments that have previously been asked for 90% CL and 5 sigma limits these are OK)

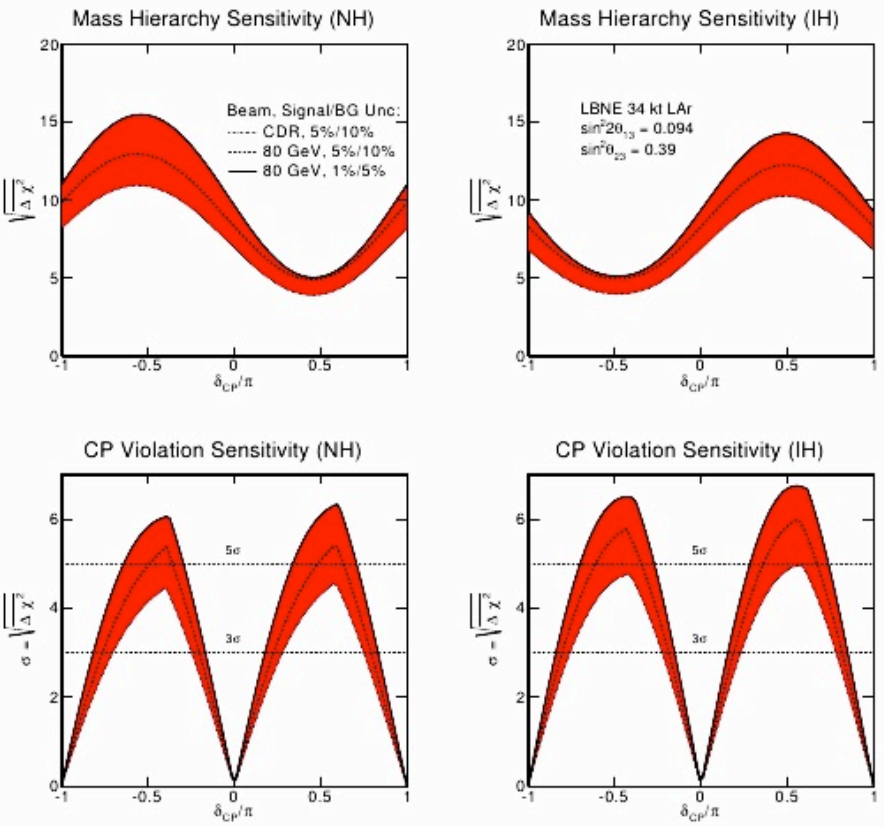


Figure 4.5: The significance with which the mass hierarchy (top) and CP violation ($\delta_{CP} \neq 0$ or π, bottom) can be determined by a typical LBNE experiment with a 34 − kt far detector as a function of the value of δ_{CP}. The plots on the left are for normal hierarchy and the plots on the right are for inverted hierarchy. The width of the red band shows the range of sensitivities that can be achieved by LBNE when varying the beam design and the signal and background uncertainties as described in the text.

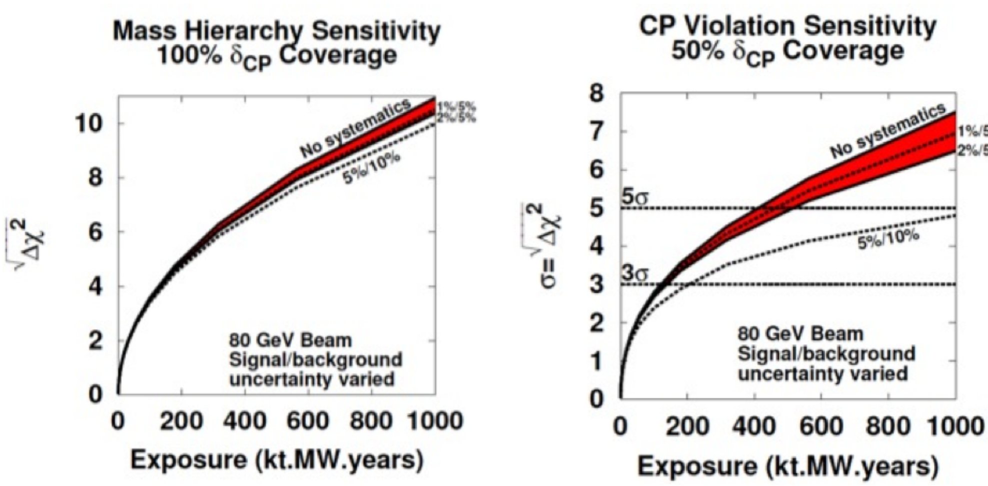


Figure 4.10: The mass hierarchy (left) and CP violation (right) sensitivities as a function of exposure in kt · year, for true normal hierarchy. The band represents the range of signal and background normalization errors.

Table 6.1: Event rates for different supernova models in 34 kt of liquid argon for a core collapse at 10 kpc, for ν_e and $\overline{\nu}_e$ charged-current channels and elastic scattering (ES) on electrons. Event rates will simply scale by active detector mass and inverse square of supernova distance.

Channel	Events *Livermore* model	Events *GKVM* model
$\nu_e + ^{40}\mathrm{Ar} \rightarrow e^- + ^{40}\mathrm{K}^*$	2308	2848
$\overline{\nu}_e + ^{40}\mathrm{Ar} \rightarrow e^+ + ^{40}\mathrm{Cl}^*$	194	134
$\nu_x + e^- \rightarrow \nu_x + e^-$	296	178
Total	**2794**	**3160**

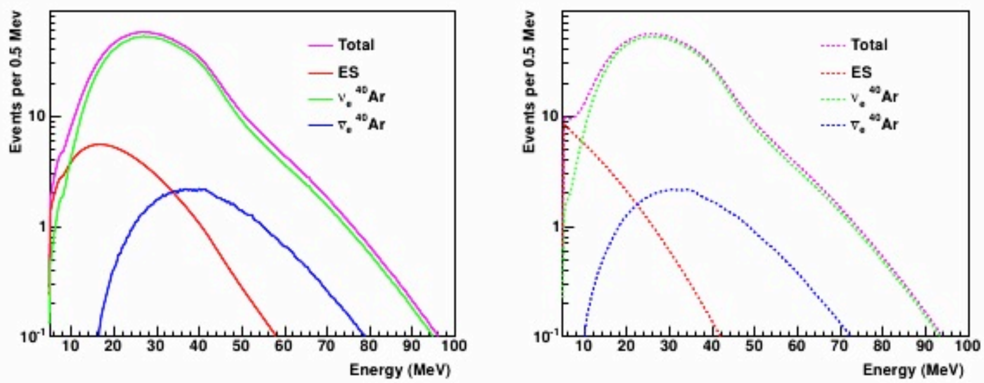


Figure 6.3: Supernova-neutrino event rates in 34 kt of argon for a core collapse at 10 kpc, for the GKVM model [222] (events per 0.5 MeV), showing three relevant interaction channels. Left: interaction rates as a function of true neutrino energy. Right: *smeared* rates as a function of detected energy, assuming resolution from [139].

d. List the sources of systematic uncertainties included in the above, their magnitudes and the basis for these estimates.

Table 4.5: The dominant systematic uncertainties on the ν_e appearance signal prediction in MINOS and T2K and a projection of the expected uncertainties in LBNE. For the MINOS uncertainties *absolute* refers to the total uncertainty and ν_e is the effect on the ν_e appearance signal only. The LBNE uncertainties are the total *expected* uncertainties on the ν_e appearance signal which include both correlated and uncorrelated uncertainties in the three-flavor fit.

Source of Uncertainty	MINOS Absolute/ν_e	T2K ν_e	LBNE ν_e	Comments
Beam Flux after N/F extrapolation	3%/0.3%	2.9%	2%	MINOS is normalization only. LBNE normalization and shape highly correlated between ν_μ/ν_e.
		Detector effects		
Energy scale (ν_μ)	7%/3.5%	included above	(2%)	Included in LBNE ν_μ sample uncertainty only in three-flavor fit. MINOS dominated by hadronic scale.
Absolute energy scale (ν_e)	5.7%/2.7%	3.4% includes all FD effects	2%	Totally active LArTPC with calibration and test beam data lowers uncertainty.
Fiducial volume	2.4%/2.4%	1%	1%	Larger detectors = smaller uncertainty.
		Neutrino interaction modeling		
Simulation includes: hadronization cross sections nuclear models	2.7%/2.7%	7.5%	$\sim 2\%$	Hadronization models are better constrained in the LBNE LArTPC. N/F cancellation larger in MINOS/LBNE. X-section uncertainties larger at T2K energies. Spectral analysis in LBNE provides extra constraint.
Total	**5.7%**	**8.8%**	**3.6 %**	**Uncorrelated ν_e uncertainty in full LBNE three-flavor fit = 1-2%.**

e. List other experiments that have similar physics goals

NOνA, T2K, LAGUNA-LBNO, T2HK

f. Synergies with other experiments.

MicroBooNE, ICARUS, CAPTAIN, LAr1-ND, LAriAT, NA-61 (hadro-production)

11. Secondary Physics Goal

   a. Expected results/sensitivity

Table 7.1: Estimated interaction rates in the neutrino (second column) and antineutrino (third column) beams per ton of detector (water) for 1×10^{20} POT at 459 m assuming neutrino cross-section predictions from NUANCE [231] and a 120−GeV proton beam using the CDR reference design. Processes are defined at the initial neutrino interaction vertex and thus do not include final-state effects. These estimates do not include detector efficiencies or acceptance [232,233].

Production mode	ν_μ Events	$\overline{\nu}_\mu$ Events
CC QE ($\nu_\mu n \to \mu^- p$)	50,100	26,300
NC elastic ($\nu_\mu N \to \nu_\mu N$)	18,800	8,980
CC resonant π^+ ($\nu_\mu N \to \mu^- N \pi^+$)	67,800	0
CC resonant π^- ($\overline{\nu}_\mu N \to \mu^+ N \pi^-$)	0	20,760
CC resonant π^0 ($\nu_\mu n \to \mu^- p \pi^0$)	16,200	6,700
NC resonant π^0 ($\nu_\mu N \to \nu_\mu N \pi^0$)	16,300	7,130
NC resonant π^+ ($\nu_\mu p \to \nu_\mu n \pi^+$)	6,930	3,200
NC resonant π^- ($\nu_\mu n \to \nu_\mu p \pi^-$)	5,980	2,570
CC DIS ($\nu_\mu N \to \mu^- X$ or $\overline{\nu}_\mu N \to \mu^+ X$, $W > 2$)	66,800	13,470
NC DIS ($\nu_\mu N \to \nu_\mu X$ or $\overline{\nu}_\mu N \to \overline{\nu}_\mu X$, $W > 2$)	24,100	5,560
NC coherent π^0 ($\nu_\mu A \to \nu_\mu A \pi^0$ or $\overline{\nu}_\mu A \to \overline{\nu}_\mu A \pi^0$)	2,040	1,530
CC coherent π^+ ($\nu_\mu A \to \mu^- A \pi^+$)	3,920	0
CC coherent π^- ($\overline{\nu}_\mu A \to \mu^+ A \pi^-$)	0	2,900
NC resonant radiative decay ($N^* \to N\gamma$)	110	50
NC elastic electron ($\nu_\mu e^- \to \nu_\mu e^-$ or $\overline{\nu}_\mu e^- \to \overline{\nu}_\mu e^-$)	30	17
Inverse Muon Decay ($\nu_\mu e \to \mu^- \nu_e$)	12	0
Other	42,600	15,800
Total CC (rounded)	**236,000**	**81,000**
Total NC+CC (rounded)	**322,000**	**115,000**

   b. List other experiments that have similar physics goals

      T2HK near detector.

12. Experimental requirements

   a. Provide requirements (neutrino source, intensity, running time, location, space,…) for each physics goal

      Initial long-baseline and near detector program: 1.2 MW 80-120 GeV energy protons to new tunable neutrino/antineutrino beamline, 10 years neutrino+antineutrino (nominal 50:50). Far detector at SURF, Lead, SD in very large cavern(s) at ~4850' underground and near detector in new hall on the Fermilab site.

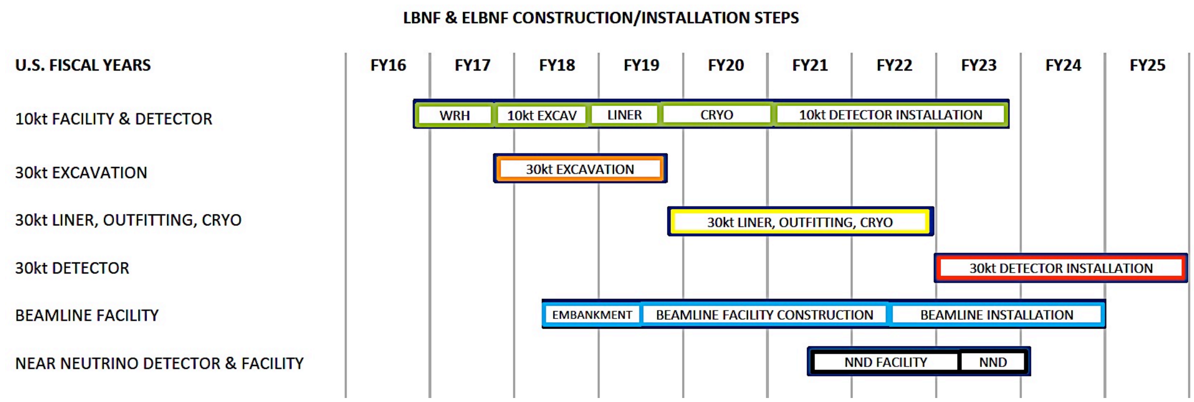
      Proton decay+Astroparticle physics program: Far detector operation independent of Fermilab accelerator complex.

13. Expected Experiment/Project time line

    a. Design and development

    b. Construction and Installation

    The timeline will be developed in consultation with the international community. Below is a concept of the timeline presented by Fermilab director Nigel Lockyer at the ELBNF collaboration meeting 1/22/15.



    c. First data

    Goal: 2021 w/ 10 kt FD; 2024 w/ full detector.

    d. End of data taking

    2034

    e. Final results

    >2034

14. Estimated cost range

    a. US contribution to the experiment/project

    ~$1B

    b. International contribution to the experiment/project

    ~$0.5B (US accounting)

    c. Operations cost

    Not yet fully developed.

15. The Future

    a. Possible detector upgrades and their motivation.

Far site: Larger mass. Higher spatial resolution for event reconstruction. Lower detection thresholds for photon detection system (e.g. below 10 MeV). Dopants in the liquid argon to improve energy resolution. Different FD technology (water, liquid scintillator, other cryogenic liquids).

These detector upgrades would be complementary to, and enhanced by, enhancements in the neutrino source such as increase beam power and flux spectrum sculpting through changes in proton beam energy and improvements in the horn/target system.

Motivation: Improved resolution on CP phase. Discovery of nucleon decay or higher statistics studies if already discovered. Higher precision on spectral shape to increase sensitivity to spectral distortions due to physics outside the 3-flavor paradigm e.g. non-standard neutrino interactions. Extend the galactic volume reach for supernova burst neutrinos; increase statistical power in spectral analyses. Measurements of solar neutrinos (day/night effect). Sensitivity to supernova relic neutrinos. Large scale dark matter search/signal investigation.

Near site: (Magnetized) Gar/LAr TPC if not implemented in the first stages. Different nuclear targets. Technology improvements identified in first running (e.g. rate capability, particle ID, reconfiguration to optimize performance with argon TPC).

Motivation: Reduce systematics for long-baseline measurements to levels required for increased far detector statistics (from higher beam power, detector mass, run time). Increase precision of neutrino interaction measurements program.

b. Potential avenues this project could open up.

   A large deep underground facility could enable a broad range of future options as described in the many DUSEL initiative documents.

   High intensity neutrino beam "Beam dump" type measurements for new particles/phenomena.